5.0   Seismic Activity Effect

Large earthquakes in populated areas often cause damage to buried pipelines. For example, the recent June 28, 1992 Richter magnitude 7.4 earthquake in the Landers/Yucca Valley area of southern California resulted in an estimated 700 breaks to water system pipelines. In general, seismic damage to buried pipelines is due to some combination of seismic wave propagation and permanent ground displacement.

Wave propagation refers to *out-of-phase* motion of a buried pipeline as seismic waves travel along the ground surface. That is, at one point in time during the shaking, one portion of a pipeline may be moving in one direction, while another portion of the line may be moving in another. Wave propagation occurs only during the ground shaking associated with a seismic event.

Permanent ground deformation refers to seismic activity which results in a permanent change to the ground profile. The four types of permanent ground deformation include:

- fault movement,
- liquefaction and subsequent lateral spreading,
- landslides, and
- subsidence.

In California, fault movement at the ground surface is usually some combination of vertical offset (the ground on one side of the fault appears to have moved upwards with respect to the ground surface on the other side of the fault) and horizontal offset (the ground on one side of the fault appears to have moved to the right or to the left with respect to the ground on the other side of the fault). For example, the 1992 Landers event resulted in roughly 1'- 6" of vertical offset and over 7'- 0" of right lateral horizontal offset near Old Woman Springs Road (State Highway 247); this movement damaged the 8 inch diameter asbestos cement water pipeline which crossed the fault.

Strong shaking of saturated sand can cause the soil to liquify. This situation is called liquefaction. Lateral spreading refers to the movement of the liquified soil mass down slope or towards a free face such as a river bank. As with fault movement, lateral spreading and landslides result in a permanent change to the soil profile.

Seismic subsidence refers to downward movements of the ground surface due to densification of subsurface soils caused by strong shaking. For example one can view dry soil as a collection of hard particles of various sizes. Like marbles in a box, the spaces between the particles are occupied by air. When shaken laterally back and forth, the particles will rearrange themselves so that some of the smaller particles move into the spaces between the bigger particles, resulting in a denser packing of the particles. This can result in a downward movement of the top surface.

As noted earlier, seismic ground movements often cause damage to buried pipelines. However, in discussing pipe damage, one must distinguish between damage to segmented versus continuous pipelines. Various earthquakes have shown that damage to segmented pipelines (e.g. bell and spigot, flange, etc. joined cast iron or asbestos cement) is much

more common than damage to continuous pipelines (e.g. full penetration welded steel).

For segmented lines, damage occurs most often at the joints, particularly for larger diameters. Typical damage mechanisms include:

- joint *pull-out* (axial extension),
- joint *crushing* (axial compression), and
- joint *bending* (angular rotation).

For modern, full penetration arc-welded pipe made of high grade steels, seismic damage is usually comprised of circumferential tearing of the pipe wall. This is caused by local buckling (the pipe in compression deforms somewhat like an *accordion*). In addition, small diameter *pin hole* leaks often occur at areas previously weakened by corrosion or prior repairs.

In this section, we will develop an estimate of expected seismic damage to California's regulated hazardous liquid pipelines. This estimate will be based upon an analysis of observed seismic damage during the study period as follows:

- The observed damage will be characterized by a plot of incidents per kilometer of pipe versus the modified Mercali Intensity (MMI) for various seismic events.

- This graph will then be combined with postulated California seismic activity for a 30 year period. The postulated activity will be based on observed seismic activity in California from 1850 through 1989 (139 years). The observed seismic activity will be characterized by a plot giving the annual probability of occurrence of various magnitude earthquakes.

- Knowing the probability of a pipe rupture for a given seismic event and the probability of such an event occurring, one can develop an estimate of the number of anticipated incidents. However, both the density of pipelines and the severity of seismic ground motion are location dependent. As a result, three scenarios will be evaluated to bracket the probable range of results.

5.1   Observed Damage

Of the roughly 500 leak incidents on California's regulated hazardous liquid pipelines during the study period, only 3 were judged to be due directly to earthquake effects.

These three leaks are summarized below. The summaries include information on the causative earthquake, its Richter magnitude, and the Modified Mercali Intensity (MMI).

The modified Mercali intensity is a subjective measure of the earthquake effects at various locations for a given event. There are a number of MMI's for an individual event. Close to the epicenter, the MMI is relatively high; as the distance from the epicenter increases, the MMI decreases, reflecting the reduction in ground shaking at these locations. On the other hand, there is only one Richter Magnitude (M) per earthquake; it is a measure of ground shaking at the epicenter.

- Leak Number 1 - On October 26, 1982, a leak in a 20" diameter, 0.250" wall thickness pipeline was reported in Fresno County. The leak was due to a crack along the lower edge of a side strap on the X-52 grade steel pipeline. The repair report notes that the opposite side of the pipe had a leak in June 1982.

   Map coordinates place the leak location about 30 miles north/northwest of the epicenter of a relatively small (local magnitude $M_L \approx 5.5$) earthquake which occurred the day before near Coalinga. The maximum MMI for this event was VI (U.S. Geological Survey Bulletin 1655). There were no recorded MMI values for the relatively sparsely populated area between the epicenter and the leak location. As a result, we have assumed that the MMI for the nearby leak site was VI.

- Leak Number 2 - On March 8, 1984, a leak in a 20" diameter, 0.250" wall thickness pipeline was reported in Fresno County. The leak was due to tearing of the pipe wall due to circumferential compression buckling or wrinkling of the X-52 grade steel pipeline.

   Map coordinates place the leak location within the area of MMI zone VIII for the May 2, 1983 Coalinga earthquake ($M_L \approx 6.3$) earthquake. Although the leak was discovered about 10 months after the earthquake, the leak description suggests that the pipe damage was likely caused by the earthquake.

- Leak Number 3 - On October 17, 1989, a leak in a 6" diameter, 0.281" wall thickness pipeline in Marin County was reported. The leak was due to cracking of a weld at a pipe bend. Map coordinates place the leak location at the boundary of an area of MMI VII for the Loma Prieta earthquake ($M_L \approx 7.0$) which occurred the day of the leak (U.S. Geological Survey Open File Report 90-18).

A summary of the data available for these three leaks is presented in Table 5-1. Fortunately, the three seismic leaks were distributed among areas with Modified Mercali Intensities of VI, VII and VIII; otherwise, the development of probable seismic incident rates may have been impossible.

5.2   Observed Leak Rate

In this section, the observed seismic damage will be characterized in terms of incidents per kilometer (km) of pipe (1.6 km = 1 mile), for various seismic events. The relative ground shaking caused by an event will be quantified using the Modified Mercali Intensity (MMI) as described earlier. Unfortunately, the small number of seismic leaks precludes a more detailed breakdown by damage mechanism (e.g. leaks per kilometer from wave propagation, leaks per kilometer from subsidence, etc.).

The earthquakes considered were taken from a table of major California and Nevada earthquakes from 1769 to 1989 (U.S. Geological Survey Professional Paper 1515). In that listing there were 17 California earthquakes for the time period from January 1, 1981 through December 31, 1990.

The observed leak rate was determined by first obtaining the total length of pipe exposed to various MMI levels for each earthquake during the study period. Then, the observed number of incidents per MMI zone, was divided by the total length of pipe exposed to corresponding MMI levels to yield the observed incident rate.

More specifically, the approximate length of pipe in the various MMI zones was determined for each of the 17 earthquakes as follows:

- The various MMI zone areas were measured for each earthquake. This was accomplished using isoseismal maps available from the U.S. Geological Survey. (See Table 5-2.)

- The length of pipe within each County was then determined. The length of each line was measured with a planimeter, using the California State Fire Marshal's roughly 1,700 Thomas Guide map book overlays and other pipeline maps available from the pipeline operators.

- The density of pipe (pipe length per unit of land area) for each County was then determined by dividing the total length of line within each County, by the area of the County itself. (See Table 5-2A.)

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Table 5-1
Seismic Leak Summary
California Regulated Hazardous Liquid Pipelines
Study Period - January 1, 1981 through January 31, 1990

Leak No.	Pipe Information				Earthquake Information			Description
	Diameter (inches)	Wall Thick (inches)	Grade	Cover (inches)	Date	MMI Epicenter	MMI Leak Site	
1	20"	0.250"	X-52	144"	October 25, 1982	VI	VI (?)	Leak along the lower edge of side strap, opposite side of pipe repaired in June 1982.
2	20"	0.250"	X-52	180"	May 2, 1983	VIII	VIII	Pipe wall tearing due to circumferential buckling.
3	6"	0.281"	N/A	54"	October 17, 1989	IX	VII	Craking of weld at pipe bend.

Table 5-2
Seismic Event Summary
California Regulated Hazardous Liquid Pipelines
Study Period - January 1, 1981 through December 31, 1990

Earthquake Number	Date of Occurrence	County Name	Local Magnitude	Affected Area (square kilometers)		
				MMI VI	MMI VII	MMI VIII
1	April 26, 1981	Imperial	5.6	1,628	625	-
2	September 4, 1981	Offshore	5.3	294	-	-
3	September 30, 1981	Mono	5.9	*	*	*
4	May 2, 1983	Fresno	6.3	9,375	2,294	625
5	July 22, 1983	Fresno	5.8	1,800	-	-
6	April 24, 1984	Santa Clara	6.2	3,000	300	-
7	September 10, 1984	Humboldt	6.6	-	-	-
8	November 23, 1984	Inyo	6.1	-	-	-
9	August 4, 1985	Fresno	5.6	750	-	-
10	July 8, 1986	San Bernardino	5.9	8,500	589	69
11	July 20, 1986	Mono	5.9	*	*	*
12	July 21, 1986	Mono	6.2	*	*	*
13	July 31, 1986	Mono	5.8	*	*	*
14	October 1, 1987	Los Angeles	5.9	2,496	704	24
15	November 24, 1987	Imperial	5.8	*	*	*
16	November 24, 1987	Imperial	6.0	*	*	*
17	October 18, 1989	Santa Cruz	7.0	21,224	6,000	533

* indicates that affected area was not calculated since no regulated hazardous liquid pipe was precent in the epicenter County.

Table 5-2A
Pipe Density By County
California Regulated Hazardous Liquid Pipelines
Study Period - January 1, 1981 through December 31, 1990

County Name	County Area (square kilometers)	Pipeline Length (kilometers)	Pipe Density (kilometers/square kilometer)
Alameda	1,905	279	0.146
Butte	4,261	46	0.011
Contra Costa	1,890	812	0.430
Fresno	15,476	580	0.037
Humboldt	9,266	2	<0.001
Kern	21,048	1,696	0.081
Kings	3,603	253	0.070
Los Angeles	10,537	3,198	0.304
Madera	5,553	54	0.010
Marin	1,354	<1	<0.001
Merced	5,033	295	0.059
Monterey	8,551	2	<0.001
Nevada	2,485	35	0.014
Orange	2,065	524	0.254
Placer	3,666	174	0.047
Riverside	18,676	520	0.028
Sacramento	2,513	147	0.058
San Bernardino	51,943	1,379	0.027
San Diego	10,910	575	0.053
San Francisco	119	2	0.019
San Joaquin	3,663	253	0.069
San Luis Obispo	8,564	761	0.089
San Mateo	1,157	44	0.038
Santa Barbara	7,114	206	0.029
Santa Clara	3,347	28	0.008
Sierra	2,483	24	0.010
Solano	2,159	148	0.068
Stanislaus	3,899	204	0.052
Sutter	1,559	17	0.011
Tulare	12,447	27	0.002
Ventura	4,820	363	0.075
Yolo	2,625	47	0.018
Yuba	1,563	35	0.022

·   An estimate of the pipe length affected by a given event was then determined by multiplying the MMI zone area by the pipe density for the county in which the epicenter was located. For the 17 earthquakes during our study period, this resulted in the values shown below. (See also Table 5-2B.)

MMI Zone VI	1,600 kilometers of pipe
MMI Zone VII	412 kilometers of pipe
MMI Zone VIII	45 kilometers of pipe

·   The observed incident rate for each MMI value was then determined by dividing the number of incidents, one each for MMI zones VI, VII and VIII, by the estimated pipe lengths for each zone (values shown above). This resulted in the following incident rates:

MMI Zone VI	0.00063 incidents per km of pipe
MMI Zone VII	0.0024 incidents per km of pipe
MMI Zone VIII	0.022 incidents per km of pipe

This methodology distinguishes between earthquakes in, for example, Imperial, Inyo or Mono counties, where there are no regulated hazardous liquid pipelines (pipe density is equal to zero), from earthquakes in Los Angeles County, where the pipe density is 0.30 kilometers of pipe per square kilometer of land area.

It is interesting to note that the average pipe density for the entire state is approximately 0.032 kilometers of pipe per square kilometer of land area (roughly 12,900 kilometers of regulated hazardous liquid pipeline over a total land area of 405,000 square kilometers). It is also interesting that the pipe densities vary widely; Los Angeles County for example has a pipe density nearly ten times the state average. (See also Table 5-2A presented earlier.)

The three incident rate data points are plotted semi-logarithmically versus MMI zone in Table 5-2C. An ordinary least squares line of best fit was prepared using the logarithm of the actual incident values; it yielded a very high R *squared* of 0.9800. (*R squared* values range from zero to one. They can be interpreted as the proportion of the variation in a given sample which is explained by the resulting regression equation; they are a comparison of the estimated systematic model with the mean of the observed values.) By extrapolation, one may expect about 0.11 incidents per kilometer of pipe for MMI zone IX areas. Once again, it should be noted that this data includes seismic damage due to all causes, *both wave propagation and permanent ground deformation.*

Table 5-2B
Estimated Pipe Lengths Exposed to Various MMI
California Regulated Hazardous Liquid Pipelines
Study Period - January 1, 1981 through December 31, 1990

Earthquake Number	County Name	Epicenter Pipe Density (km/km²)	Estimated Pipe Length (kilometer)		
			MMI VI +	MMI VII +	MMI VIII +
1	Imperial	0.000	-	-	-
2	Offshore	0.304	89.2	-	-
3	Mono	0.000	-	-	-
4	Fresno	0.037	350	85.5	23.3
5	Fresno	0.037	67.1	-	-
6	Santa Clara	0.008	26.1	2.61	-
7	Humboldt	<0.001	-	-	-
8	Inyo	0.000	-	-	-
9	Fresno	0.054[1]	40.3	-	-
10	San Bernardino	0.027	227	15.7	1.8
11	Mono	0.000	-	-	-
12	Mono	0.000	-	-	-
13	Mono	0.000	-	-	-
14	Los Angeles	0.304	757	213	7.3
15	Imperial	0.000	-	-	-
16	Imperial	0.000	-	-	-
17	Santa Cruz	0.023[2]	495	140	12.4
		Totals[3]	2,051.7	456.8	44.8

[1] The epicenter was located at the Fresno and Kings County border. The average pipe density for these counties was used.
[2] MMI VII was recorded in both Santa Clara and San Mateo Counties. The average pipe density for these counties was used.
[3] To determine the length within each individual MMI zone, the length within the next group of zones must be subtracted. For example, the length of pipe in MMI = VI is 2,051.7 - 456.8 = 1,594.9.

Table 5-2C
Seismic Incident Rates
California Regulated Hazardous Liquid Pipelines
Study Period — January 1, 1981 through December 31, 1990

Modified Mercali Intensity	Actual Incident Rate (incidents per kilometer of pipe)	Straight Line Fit (incidents per kilometer of pipe)
VI	0.00063	0.00054
VII	0.0024	0.0032
VIII	0.022	0.019
IX	N/A	0.11

Seismic Incident Rate Comparison
Incidents Per Kilometer of Pipe
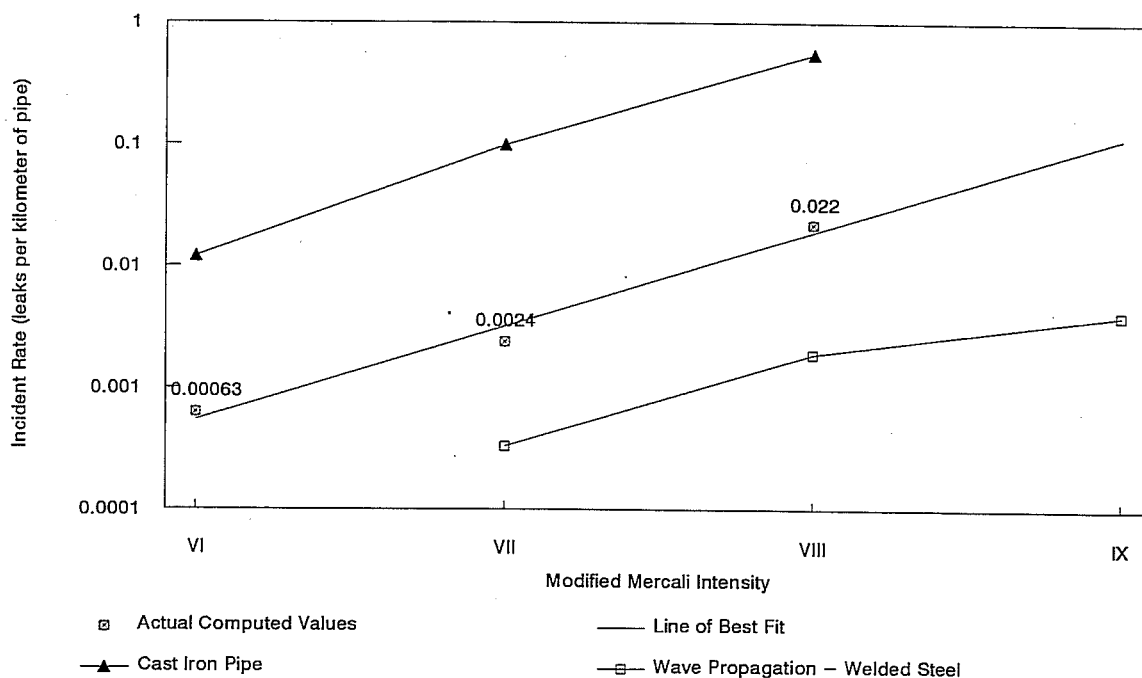
Two other relations are also shown in Figure 5-2C. The upper relation (O'Rourke et al) is for seismic damage to cast iron pipe due to all causes (wave propagation and permanent ground deformation). The lower relation (Eguchi) is for seismic damage to steel pipe with arc-welded joints due to wave propagation only. Hence the seismic leak rate developed herein is reasonable, since it falls within the expected range. That is, the incident rate for all causes for regulated California hazardous liquid pipelines is less than that for segmented cast iron pipe. Similarly, the incident rate for regulated California hazardous liquid pipelines due to all causes is greater than that for wave propagation damage only to welded steel pipe.

5.3   Future Seismic Activity

The expected seismic activity in California for a future 30 year period has been based herein on observed earthquakes in California from 1850 through 1989. In other words, we have assumed that the underlying rate of earthquake occurrence will not change. The U. S. Geological Survey's listing of major California and Nevada earthquakes, 1769-1989 (U.S. Geological Survey Profession Paper 1515 mentioned previously), was used to identify California earthquakes during the selected 130 year period. Activity prior to 1850 was excluded since some quakes may have been missed due to the sparse population.

The number of earthquakes with magnitudes greater than, or equal to various values for the 139 year period from 1850 through 1989 are shown in Table 5-3. For example, there were 38 earthquakes during that period with a magnitude $M_L \geq 6.5$. Hence, the annual occurrence rate for earthquakes with $M_L \geq 6.5$ is 0.27 earthquakes per year (38 earthquakes/139 years). That is, on an average, one would expect a $M_L \geq 6.5$ seismic event somewhere in California roughly every 3.7 years (1 event/0.27 earthquakes per year).
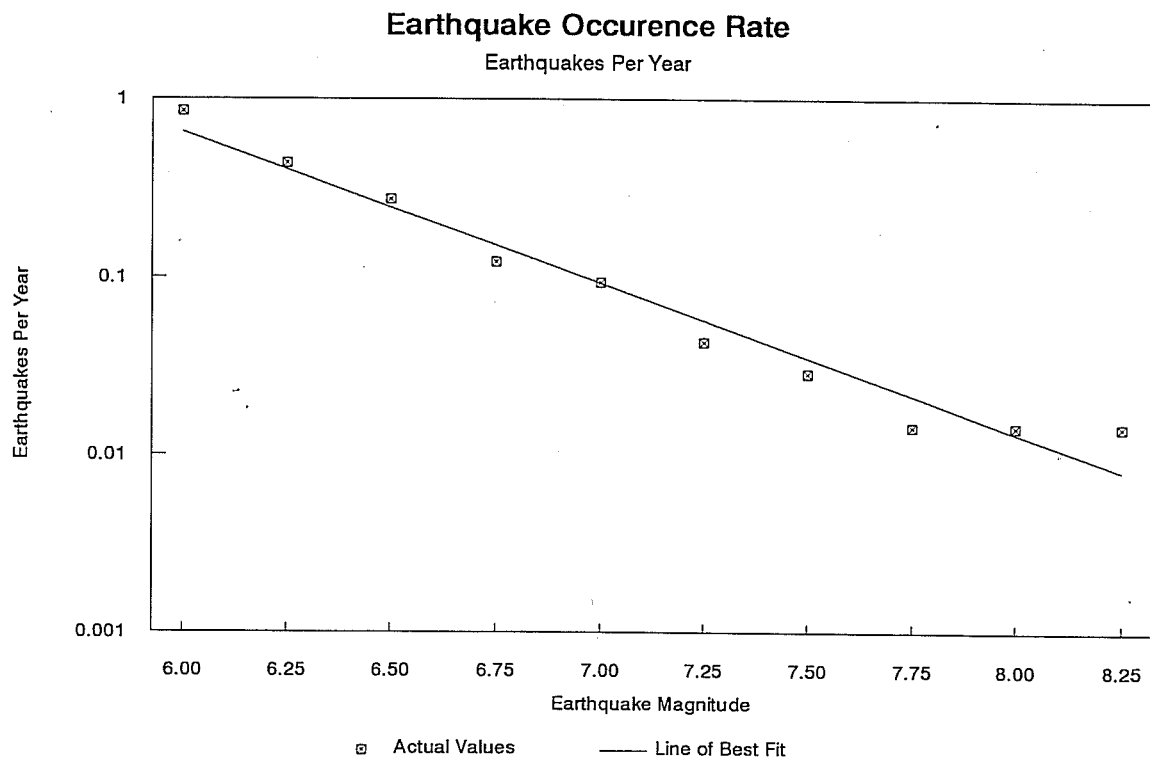
The annual occurrence rate data have been plotted semi-logarithmically versus earthquake magnitude in Table 5-3 for all quakes with a Richter magnitude greater than or equal to 6.0. The ordinary least squares line of best fit of the logarithm of the actual occurrence rates yielded an R squared of 0.9633. As explained earlier, this near unity value indicates very strong linearity and little statistical variation. The fitted straight line values shown in Table 5-3 will be used to estimate the likelihood of California's seismic activity for a future 30 year period.

The largest earthquake expected during a 30 year period would have an annual occurrence rate of 0.033 events per year (1 event/30 years). From the straight line fit data shown in Table 5-3, an annual occurrence rate of 0.033 corresponds to a California event with a magnitude of about 7.5. Hence, the largest earthquake expected during a future 30 year period is an event with a magnitude of 7.5 or larger. The table below lists the estimated annual frequency of occurrence and the anticipated number of events during a future 30 year period for various events.

Table 5-3
Annual Occurence Rate For California Earthquakes
Based on 1850-1989 U.S. Geological Survey Data

Richter Magnitude	No. of Events with Magnitude Greater Than or Equal To	Actual Occurence Rate (Events per Year)	Straight Line Fit (Events per Year)
6.00	118	0.849	0.655
6.25	61	0.439	0.402
6.50	38	0.273	0.247
6.75	17	0.122	0.152
7.00	13	0.094	0.093
7.25	6	0.043	0.057
7.50	4	0.029	0.035
7.75	2	0.014	0.022
8.00	2	0.014	0.013
8.25	2	0.014	0.008

Earthquake Occurence Rate

Earthquakes Per Year

Actual Values   —— Line of Best Fit

Event Magnitude (M)	Annual Occurrence Rate (events per year)	Anticipated Number of Events During 30 Year Period
≥ 7.5	0.035	1
≥ 7.0	0.093	3
≥ 6.5	0.247	7
≥ 6.0	0.655	20

We have assumed that the one earthquake expected during a future 30 year period with a magnitude greater than 7.5 would have a local magnitude $M_L \approx 7.75$. The number of events for each of the other magnitudes has been determined by simple subtraction. For example, since we expect 20 events with a magnitude greater than or equal to 6.0, and 7 events with a magnitude greater than or equal to 6.5, we can expect 13 (20 minus 7) events with a local magnitude $M_L \approx 6.25$. The actual number of events expected during a future 30 year period for various magnitudes have been determined in the same manner; these values are shown below.

Local Magnitude (M_L)	Number of Events
7.75	1
7.25	2
6.75	4
6.25	13

5.4   Expected Seismic Incidents

In this section, the number of California hazardous liquid pipeline incidents which are likely to be caused by seismic activity during a 30 year period will be estimated. This will be accomplished by combining the empirical incident rates given in Table 5-2C with the anticipated number of earthquakes during the next 30 years as presented above.

The length of hazardous liquid pipelines exposed to various levels of Modified Mercali Intensities (MMI) can be estimated by multiplying the pipeline density (pipe length per unit land area), by the land area of various MMI zones for different magnitude earthquakes. The following empirical formulas (Toppozada, 1975) relate local magnitude (M_L) (assumed to be equivalent to Richter magnitude M for this study), to the land area shaken at or above various MMI values.

$$M_L = 2.56 + 0.85 \, \mathrm{Log} \, (A_{VI+}) \tag{1}$$

$$M_L = 3.49 + 0.87 \text{ Log } (A_{VII+}) \qquad (2)$$

$$M_L = 4.30 + 0.87 \text{ Log } (A_{VIII+}) \qquad (3)$$

where: A_{VI+} is the land area in square kilometers having an MMI of VI+ or larger, etc.

For example, equation (2) suggests that about 21,000 square kilometers would experience a modified Mercali intensity of VII or larger for a $M_L = 7.25$ event.

The total areas from equations (1) through (3) must be reduced to account for the fact that earthquakes along the coast or near the state border would generate smaller areas of MMI *within the state* than the equations would indicate. A reduction has been developed based upon a comparison between the measured MMI zone areas for the 1981 through 1990 period with corresponding areas predicted by equations (1) through (3). On average, this comparison suggests that the actual land area *within the state* is roughly one-fifth of the values predicted by the empirical equations. The areas expected to experience various levels of ground shaking are shown in Table 5-2B.

In addition, a relation similar to those in equations (1) through (3) was developed for MMI zone areas for MMI greater than or equal to IX; this was done by noting that shaken areas reduce by a factor of about 10, for a unit increase in MMI. In other words, for a given magnitude event, the area shaken at MMI $\geq$ VII is roughly ten times larger that the area shaken at MMI $\geq$ VIII. The actual equation used is shown below:

$$A_{IX+} \approx \{0.10A_{VIII+} + 0.01A_{VII+} + 0.001A_{VI+}\} \div 3$$

The Table 5-4 values, from equations (1) through (3) modified as described above, have been multiplied by the number of anticipated events of each magnitude to determine the estimated total area which may be expected to experience various levels of ground shaking. This data is shown in Table 5-4A.

The resulting cumulative total land area in California expected to be shaken at specific MMI levels during a 30 year period are as follows:

- MMI = IX   346 km²
- MMI = VIII   3,810 km²
- MMI = VII   32,500 km²
- MMI = VI   512,000 km²

Table 5-4
Emperical Areas Exposed to Various Modified Mercali Intensities Versus Local Earthquake Magnitude
(Values Shown are One-Fifth Toppozada Values)

Local Richter Magnitude	Affected Area (square kilometers)			
	MMI VI+	MMI VII+	MMI VIII+	MMI IX+
6.00	2,229	153	18	2
6.25	4,387	297	35	3
6.50	8,636	577	68	6
6.75	17,000	1,117	131	12
7.00	33,463	2,165	254	23
7.25	65,868	4,196	492	45
7.50	129,657	8,133	953	87
7.75	255,219	15,761	1,847	170
8.00	502,377	30,545	3,580	332

Table 5-4A
30 Year Estimate of California Earthquakes
Areas Affected By Various Sized Events

Estimated Number of Seismic Events	Local Magnitude	Estimated Area (square kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
1	7.75	255,219	15,761	1,847	170
2	7.25	131,737	8,393	984	89
4	6.75	67,999	4,469	524	47
13	6.25	57,036	3,867	453	40
Total		511,990	32,490	3,808	346

The expected seismic damage to hazardous liquid pipelines is a function of the pipe density in the region. For example, no damage would be expected from earthquakes in Inyo County, (location of the March 26, 1872, Richter magnitude M=7.6 Owen Valley event) or Imperial County (location of the May 18, 1940, Richter magnitude M=7.1 Imperial Valley event) since these counties have no hazardous liquid pipelines (pipe density equals zero). On the other hand, more damage would be expected from an earthquake in Los Angeles County (pipe density = 0.30 kilometers of pipe per square kilometer of land area) or Orange County (pipe density = 0.25 kilometers of pipe per square kilometer of land area).

To bracket the possible results to account for the uncertain nature of the epicenter locations, we will consider three scenarios. Each scenario will include different pipe densities. The number and magnitude of events during the 30 year period will be as presented earlier in Section 5.3.

- Scenario Number 1 - Assume that the epicenter and corresponding MMI zones IX and VIII for the one $M_L \approx 7.75$ event lie in a region with a pipe density of 0.28 kilometers of pipe per square kilometer of land area (similar to Los Angeles and Orange Counties). The other MMI zone areas for the one $M_L \approx 7.75$ event and for all other events (three $M_L \approx 7.25$, seven $M_L \approx 6.75$, and eighteen $M_L \approx 6.25$ events) assume the state wide pipe density average of 0.031 kilometers of pipe per square kilometer of land area.

- Scenario Number 2 - This scenario assumes that all events and all MMI zone areas occur in regions with the state average pipe density of 0.031 kilometers of pipe per square kilometer of land area.

- Scenario Number 3 - Finally, this scenario assumes that the epicenter and corresponding MMI zones IX and VIII for the one $M_L \approx 7.75$ event lie in a region with a pipe density of 0.00 kilometers of pipe per square kilometer of land area (such as Inyo and Imperial Counties). The other MMI zone areas for the one $M_L \approx 7.75$ event and for all other events (three $M_L \approx 7.25$, seven $M_L \approx 6.75$, and eighteen $M_L \approx 6.25$ events) assume the state wide pipe density average of 0.031 kilometers of pipe per square kilometer of land area.

A summary of this data is included in Tables 5-4B, C and D. The estimated number of California hazardous liquid pipeline incidents caused by seismic activity during a future 30 year period are summarized shown below:

MMI Zone	Scenario No. 1 (No. Incidents)	Scenario No. 2 (No. Incidents)	Scenario No. 3 (No. Incidents)
VI	8.57	8.57	8.57
VII	3.22	3.22	3.22
VIII	10.98	2.24	1.16
IX+	5.84	1.18	0.60
Total	28.61	15.21	13.55
Estimated Injuries	2.72	1.45	1.29
Estimated Fatalities	0.17	0.09	0.08

As indicated, we anticipate somewhere between 13 and 29 California hazardous liquid pipeline incidents being caused by seismic activity during a future 30 year period. During the ten year study period, the number of injuries was approximately 9.5% of the number of incidents; the number of fatalities was approximately 0.58% of the number of incidents. Extrapolating these data, we could estimate that seismic activity during a future 30 year period may cause between one and three injuries and may have between a 1 in 6 and 1 in 13 likelihood of causing a fatality.

Table 5-4B
Various Scenarios - Seismic Incident Estimates
California Regulated Hazardous Liquid Pipelines

Scenario 1 - Affected Areas

Estimated Number of Seismic Events	Local Richter Magnitude	Estimated Area (square kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
1	7.75	0	0	1,847	170
1	7.75	255,219	15,761	0	0
2	7.25	131,737	8,393	984	89
4	6.75	67,999	4,469	524	47
13	6.25	57,036	3,867	453	40

Scenario 1 - Estimated Affected Pipe Lengths

Local Richter Magnitude	Pipe Density (km/km²)	Estimated Pipe Length (kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
7.75	0.280	0	0	517	48
7.75	0.031	7,912	489	0	0
7.25	0.031	4,084	260	31	3
6.75	0.031	2,108	139	16	1
6.25	0.031	1,768	120	14	1

Scenario 1 - Estimated Number of Incidents

Local Richter Magnitude	Incident Rate	Estimated Number of Incidents (incidents per 30 years)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
		0.00054	0.0032	0.019	0.11
7.75		0.00	0.00	9.83	5.34
7.75		4.27	1.56	0.00	0.00
7.25		2.21	0.83	0.58	0.30
6.75		1.14	0.44	0.31	0.16
6.25		0.95	0.38	0.27	0.14
Total		8.57	3.22	10.98	5.84

Table 5-4C
Various Scenarios - Seismic Incident Estimates
California Regulated Hazardous Liquid Pipelines

Scenario 2 - Affected Areas

Estimated Number of Seismic Events	Local Richter Magnitude	Estimated Area (square kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
1	7.75	255,219	15,761	1,847	170
3	7.25	131,737	8,393	984	89
7	6.75	67,999	4,469	524	47
18	6.25	57,036	3,867	453	40

Scenario 2 - Estimated Affected Pipe Lengths

Local Richter Magnitude	Pipe Density (km/km²)	Estimated Pipe Length (kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
7.75	0.031	7,912	489	57	5
7.25	0.031	4,084	260	31	3
6.75	0.031	2,108	139	16	1
6.25	0.031	1,768	120	14	1

Scenario 2 - Estimated Number of Incidents

Local Richter Magnitude	Incident Rate	Estimated Number of Incidents (incidents per 30 years)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
		0.00054	0.0032	0.019	0.11
7.75		4.27	1.56	1.09	0.58
7.25		2.21	0.83	0.58	0.30
6.75		1.14	0.44	0.31	0.16
6.25		0.95	0.38	0.27	0.14
Total		8.57	3.22	2.24	1.18

Table 5-4D
Various Scenarios - Seismic Incident Estimates
California Regulated Hazardous Liquid Pipelines

Scenario 3 - Affected Areas

Estimated Number of Seismic Events	Local Richter Magnitude	Estimated Area (square kilometers)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
1	7.75	0	0	1,847	170
1	7.75	255,219	15,761	0	0
3	7.25	131,737	8,393	984	89
7	6.75	67,999	4,469	524	47
18	6.25	57,036	3,867	453	40

Scenario 3 - Estimated Affected Pipe Lengths

Local Richter Magnitude	Pipe Density (km/km²)	Estimated Pipe Length (kilometers)			
		MMI VI+	MMI VII+	MMI VIII+	MMI IX+
7.75	0.280	0	0	0	0
7.75	0.031	7,912	489	0	0
7.25	0.031	4,084	260	31	3
6.75	0.031	2,108	139	16	1
6.25	0.031	1,768	120	14	1

Scenario 3 - Estimated Number of Incidents

Local Richter Magnitude	Incident Rate	Estimated Number of Incidents (incidents per 30 years)			
		MMI VI	MMI VII	MMI VIII	MMI IX+
		0.00054	0.0032	0.019	0.11
7.75		0.00	0.00	0.00	0.00
7.75		4.27	1.56	0.00	0.00
7.25		2.21	0.83	0.58	0.30
6.75		1.14	0.44	0.31	0.16
6.25		0.95	0.38	0.27	0.14
Total		8.57	3.22	1.16	0.60